Update on Experiment to Model and Calibrate Pavement Structural Effects on Vehicle Fuel Economy and GHG Emissions

Participants:
University of California Pavement Research Center
Michigan State University
Massachusetts Institute of Technology Concrete Sustainability Hub
Oregon State University
University of Minnesota
Symplectic Engineering Corporation

Sponsored by:
California Department of Transportation
with assistance from Minnesota Department of Transportation

PAVEMENT LCA 2014

Phase I Tasks

- **I:1** Identify participating modelers, review models.
  - Completed
- **I:2** Identify test sections, measure pavement characteristics needed by modelers, and other characteristics affecting fuel economy.
  - 22 sections identified
  - Field deflection, IRI and MPD measurements completed twice (cool, hot conditions)
  - Laboratory shear frequency sweep tests as cross-check on viscoelastic high temp properties
  - Completed

Phase I Tasks

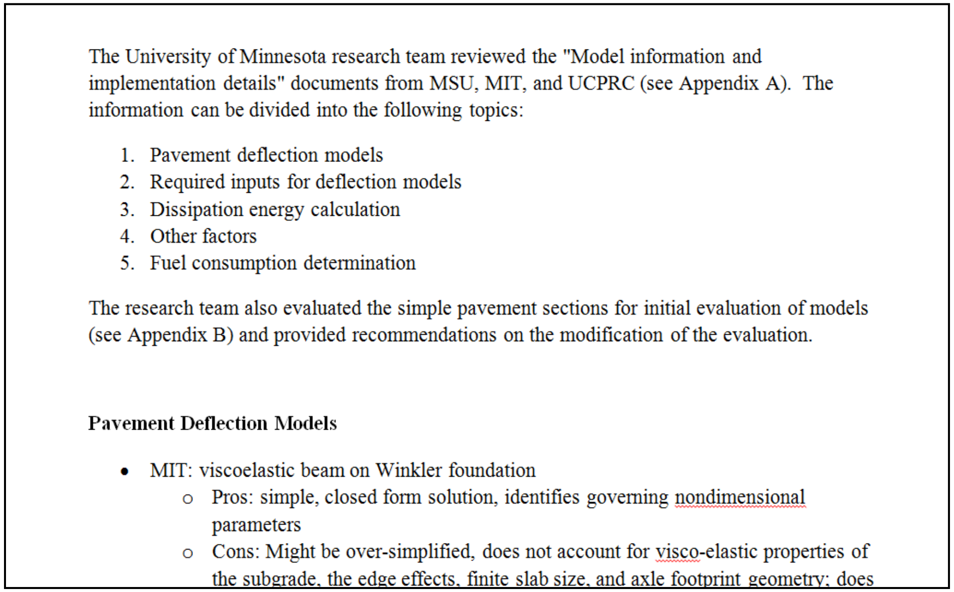
- **I:3** Compare modeling results for test sections
  - Initial comparison of deflections, energy dissipation, fuel use for example pavements, completed
  - Back-calculation of elastic and viscoelastic properties for test sections (MSU), completed
  - Calculations of deflections, energy dissipation, differences in vehicle fuel economy for structural response, roughness, MPD, currently underway, expected completion 1 Dec 2014
- **I:4** Prepare experimental plan for validation of modeling results: December 2014
- **I:5** Communicate results of Phase I: January 2015
- **I:6** Summarize results of Phase I: January 2015

Model Approaches

- UCPRC (implementation of Lyon)
  - Viscoelastic energy dissipation in asphalt on elastic underlying layers
  - 3-D finite element implementation
- Massachusetts Institute of Technology
  - Energy consumption in vehicle due to viscoelastic top layer (wheel rolling up hill calculated with gradient at wheel location in a moving coordinate system)
  - Viscoelastic beam implementation and elastic subgrade
  - Intended primarily for network use after calibration with finite element solutions
- Michigan State University
  - Energy consumption in vehicle due to viscoelastic top layer on elastic underlying layers (wheel rolling up hill calculated with average gradient of bowl)
  - Axisymmetric finite element implementation

Outside review of models and implementation by L. Khazanovich and S. Weissman, funded by MnDOT

- Review of assumptions, implementation
- Recommendations
  - for improving implementation
  - for future improvements to models



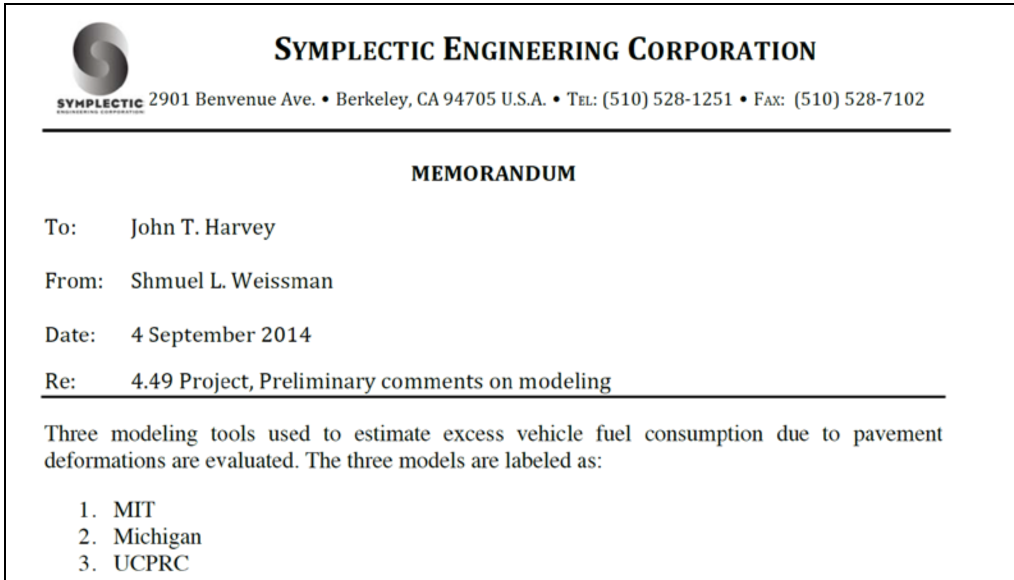
The University of Minnesota research team reviewed the "Model information and implementation details" documents from MSU, MIT, and UCPRC (see Appendix A). The information can be divided into the following topics:

1. Pavement deflection models
2. Required inputs for deflection models
3. Dissipation energy calculation
4. Other factors
5. Fuel consumption determination

The research team also evaluated the simple pavement sections for initial evaluation of models (see Appendix B) and provided recommendations on the modification of the evaluation.

Pavement Deflection Models

- MIT: viscoelastic beam on Winkler foundation
  - Pros: simple, closed form solution, identifies governing nondimensional parameters
  - Cons: Might be over-simplified, does not account for visco-elastic properties of the subgrade, the edge effects, finite slab size, and axle footprint geometry; does



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MEMORANDUM

To: John T. Harvey

From: Shmuel L. Weissman

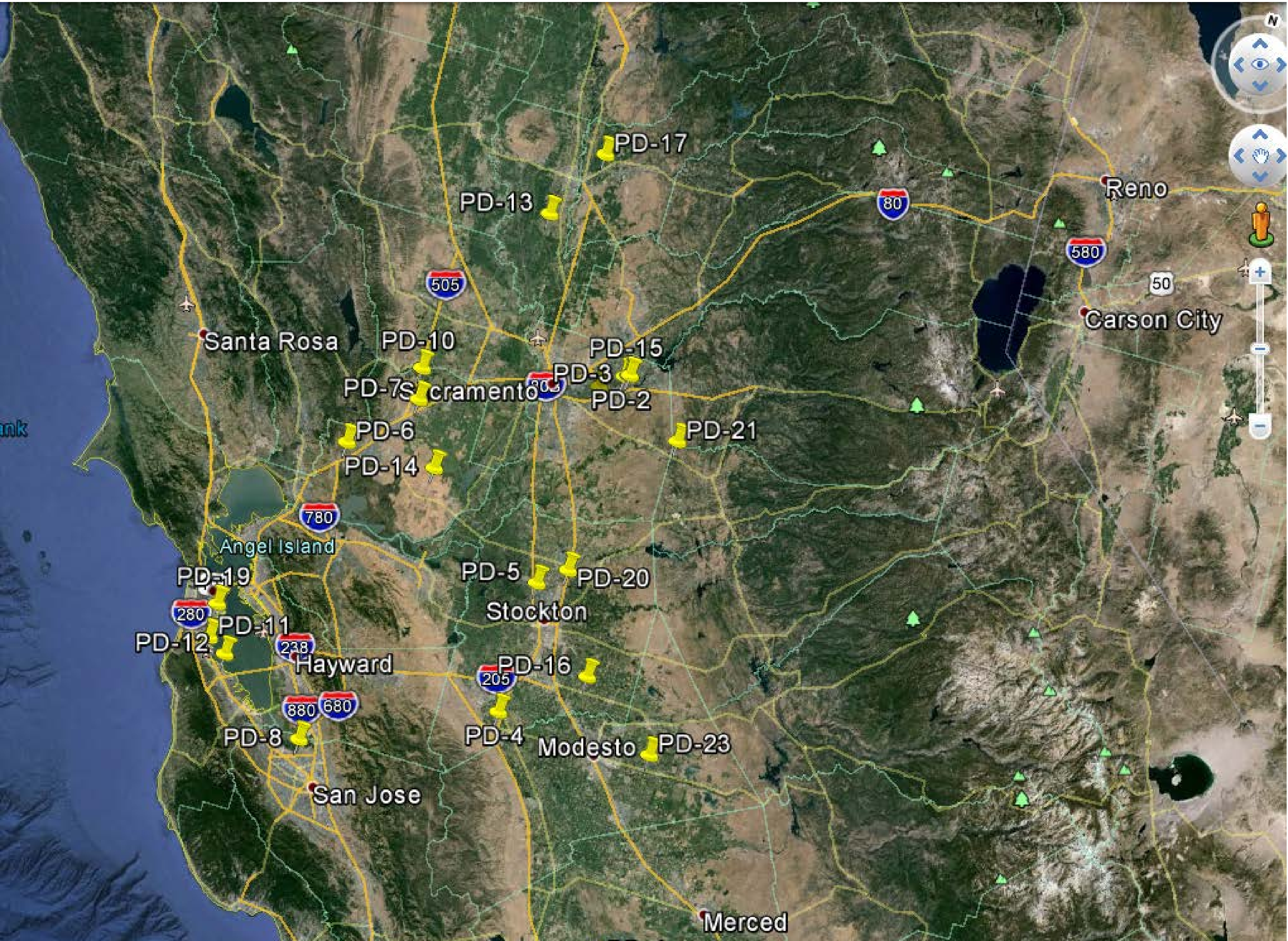
Date: 4 September 2014

Re: 4.49 Project, Preliminary comments on modeling

Three modeling tools used to estimate excess vehicle fuel consumption due to pavement deformations are evaluated. The three models are labeled as:

1. MIT
2. Michigan
3. UCPRC

	1 Max deflection at the bottom of the basin	2 Average slope under contact area	3 Dissipated energy in pavement (stress and strain)	4 Power from gradient compared to no gradient from HDM-4	3 Excess fuel consumption	4 Energy from profile or IRI	5 Energy from macrotexture
Michigan State University	X (calibrate elastic cases w/LET)	X		X	X using Col. 2, 4 results	X NCHRP 720 eqtn + simulation model	X NCHRP 720 eqtn
MIT	X (not calibrated) not used directly for energy calc in Gen II	X not used directly for energy calc in Gen II	X		X from Gen II model	X approach using profile	
UCPRC	X (calibrate elastic cases w/LET)	X	X		X using Col. 3 resluts	X NCHRP 720 eqtn	NCHRP 720 eqtn


N
PD-17
Reno
PD-13
80
580
505
50
Santa Rosa
Carson City
PD-10
PD-15
PD-3
PD-7
Sacramento
PD-2
ank
PD-6
PD-21
PD-14
780
Angel Island
PD-19
PD-5
PD-20
280
PD-11
Stockton
PD-12
238
Hayward
PD-16
205
880
680
PD-8
PD-4
Modesto
PD-23
San Jose
Merced

Section	Structure and Surface Type	Approx H_{top} (mm) GPR/coring	Sub grade	Length (km)	Slope	avg IRI	MPD
PD-01	Concrete (JPCP)	222	Clay	0.94	-0.04%	1.16	0.29
PD-02	Concrete (JPCP) (Dowelled)	208	sand	0.63	0.10%	0.97	0.23
PD-03	Concrete (JPCP)	196	Sand	0.75	-0.04%	1.17	0.33
PD-04	Concrete (JPCP)	280	Any	0.63	0.17%	3.08	0.36
PD-05	Concrete (CRC)	TBD	Any	0.75	0.06%	1.15	0.51
PD-06	HMA-O HMA	36 268	Sand	1.19	-0.09%	1.56	1.69
PD-07	RHMA-G PCC	146 224	Sand	0.81	0.09%	0.82	1.63
PD-08	HMA-O HMA PCC	35 117 278	Clay	0.38	-0.10%	1.54	1.37
PD-10	RHMA-G HMA PCC	86 196 233	Sand	0.81	-0.06%	0.97	1.67
PD-11	HMA-O HMA	41 244	Clay	0.63	0.05%	1.22	2.06
PD-12	HMA-O HMA	37 139	Clay	0.63	-0.02%	1.32	1.01

Section	Structure and Surface Type	Approx H_{top} (mm) GPR/coring	Sub grade	Length (km)	Slope	avg IRI	MPD
PD-13	HMA	391	Clay	0.63	0.13%	1.37	0.73
PD-14	HMA	233	Clay	0.63	-0.49%	3.57	0.70
PD-15	RHMA-O HMA	31 193	Sand	1.13	0.08%	0.95	2.05
PD-16	HMA-G HMA	41 231	Sand	0.63	0.12%	0.97	0.93
PD-17	HMA	210	Any	0.44	-0.01%	1.37	0.66
PD-18	RHMA-G HMA	29 226	Sand	0.63	-0.08%	0.65	0.85
PD-19	RHMA-G HMA	65 168	Any	0.75	0.01%	0.95	0.84
PD-20	RHMA-G HMA CTB	43 115 217	Clay	0.50	-0.02%	1.72	2.13
PD-21	HMA-O HMA CTB	30 124 235	Clay	0.38	1.01%	1.51	1.84
PD-22	RHMA-G HMA CTB	43 246 124	Clay	0.56	0.25%	1.20	0.74
PD-23	HMA CTB	274 146	Sand	0.63	-0.11%	0.88	0.80

Day and night FWD testing

- Temperature measured to 200 mm depth in AC for back-calculations

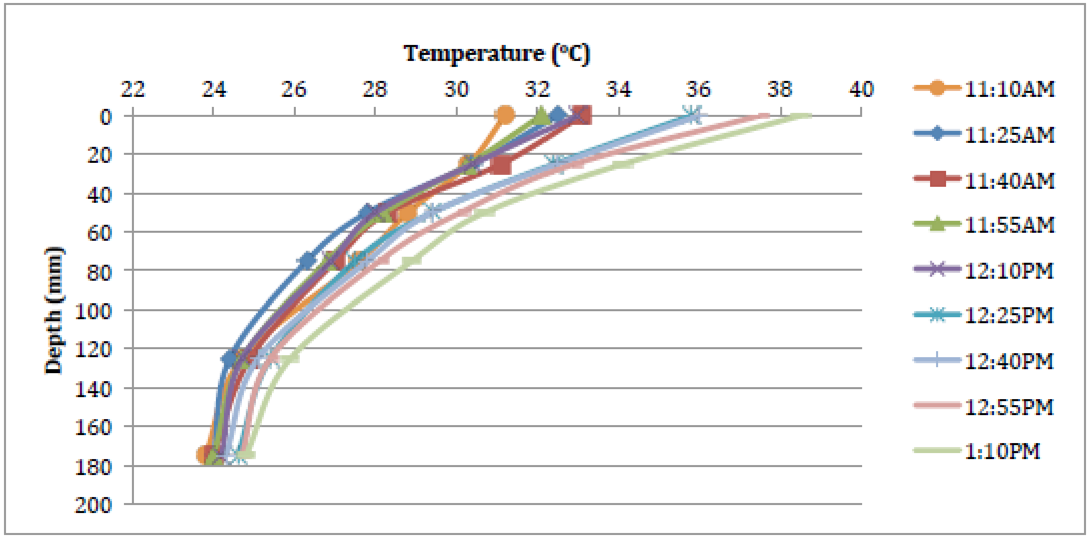


Figure 3: Daytime Temperature (°C) vs. Depth (mm)

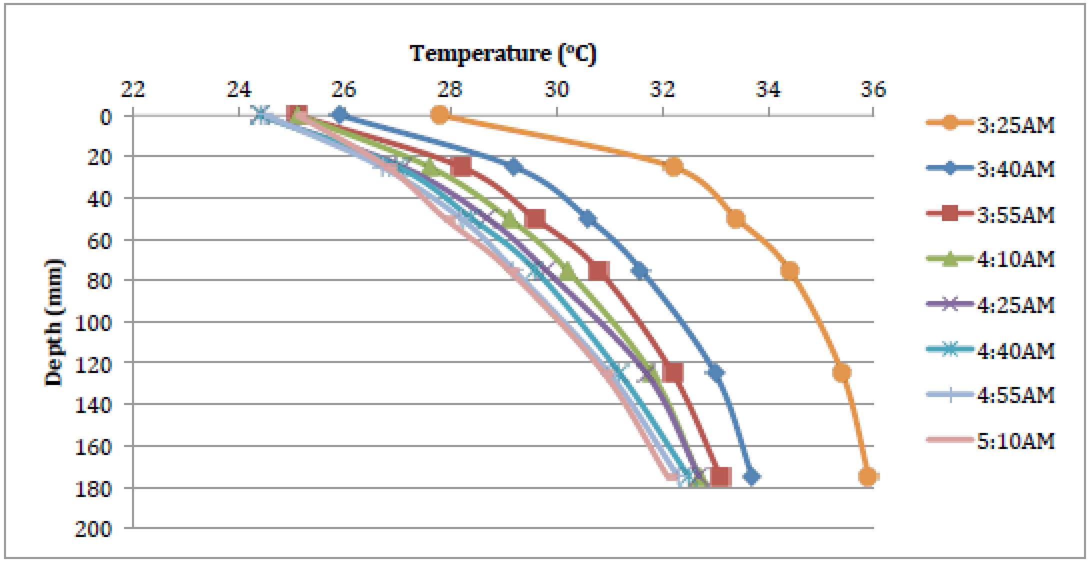


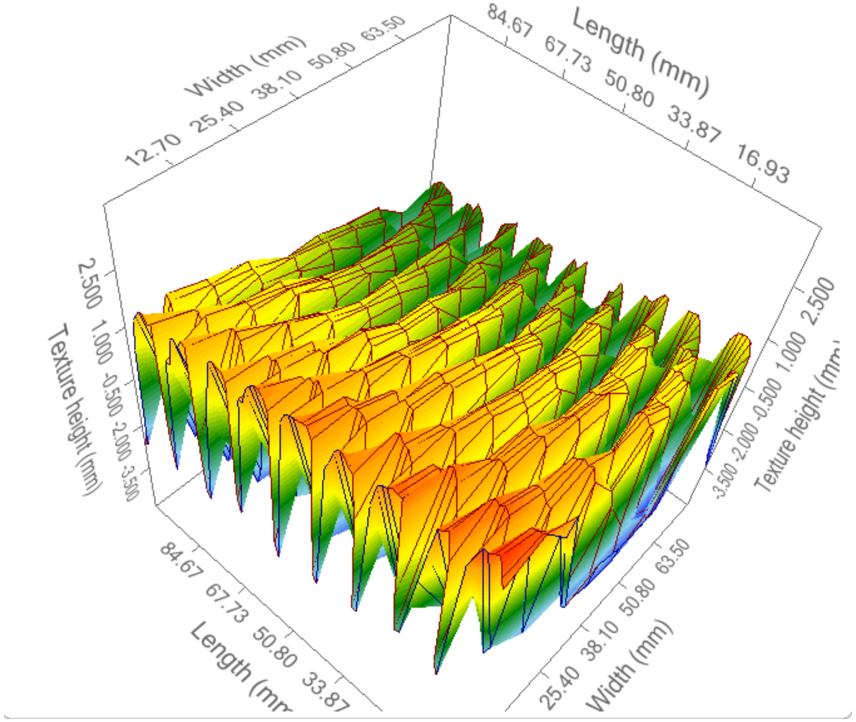
Figure 4: Nighttime Temperature (°C) vs. Depth (mm)

Lab Testing

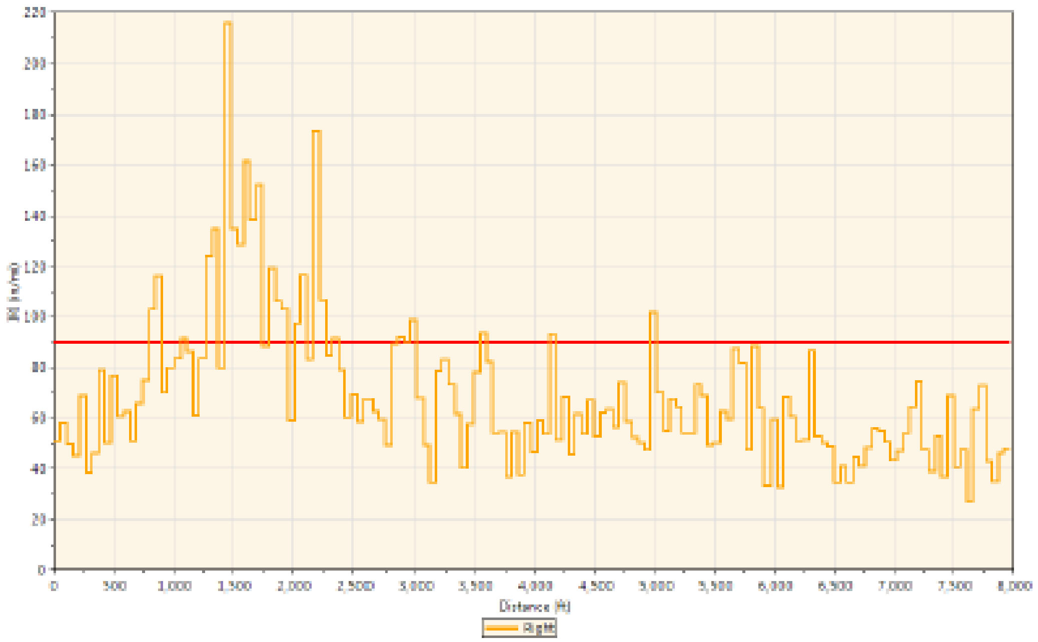
- Shear frequency sweeps on upper layers of AC sections for comparison with back-calculated values

Field Testing

- MPD and MTD from Laser Texture Scanner



IRI from inertial profiler day and night



The MPD values measured along the section are shown in Figure 8.

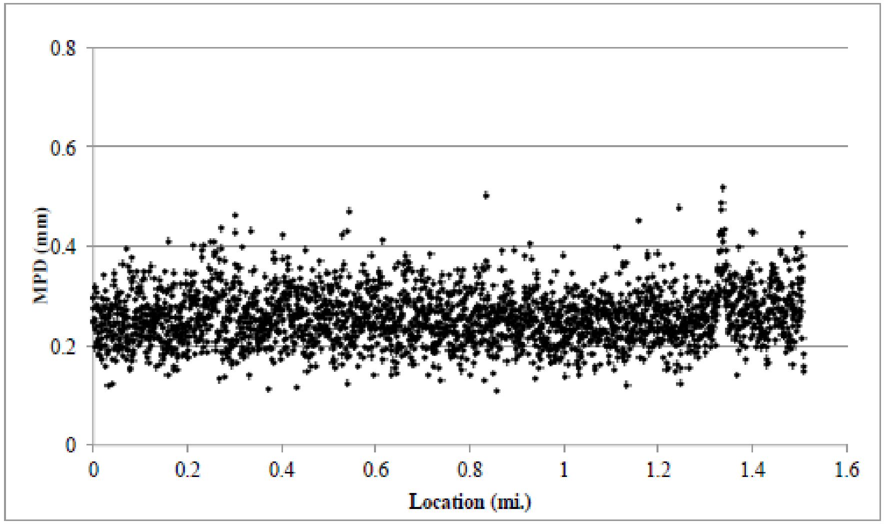
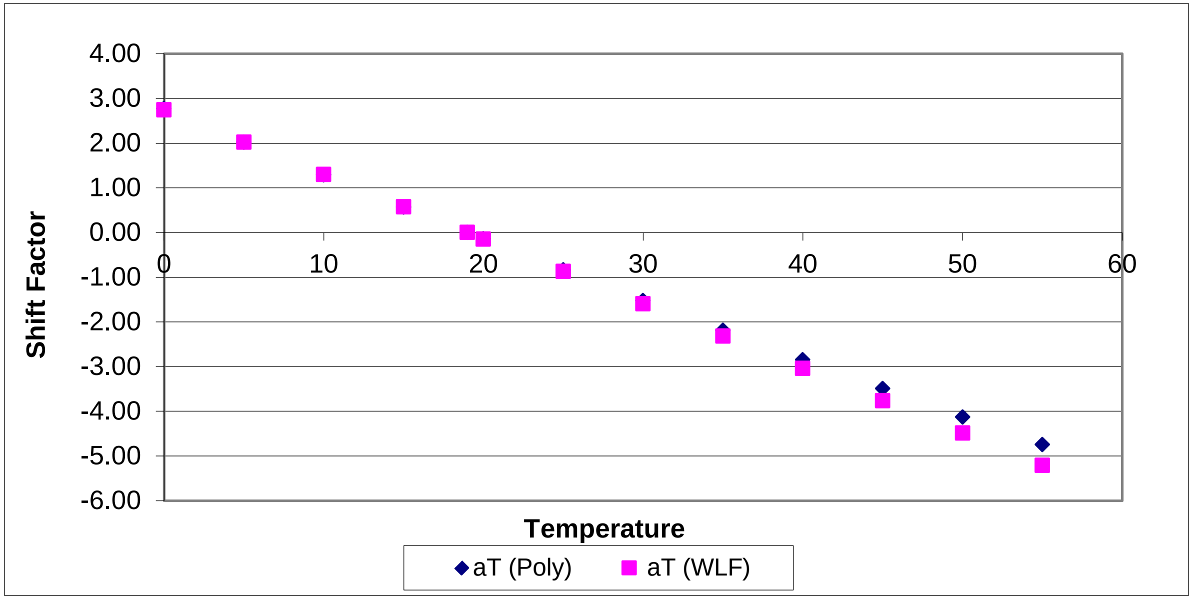


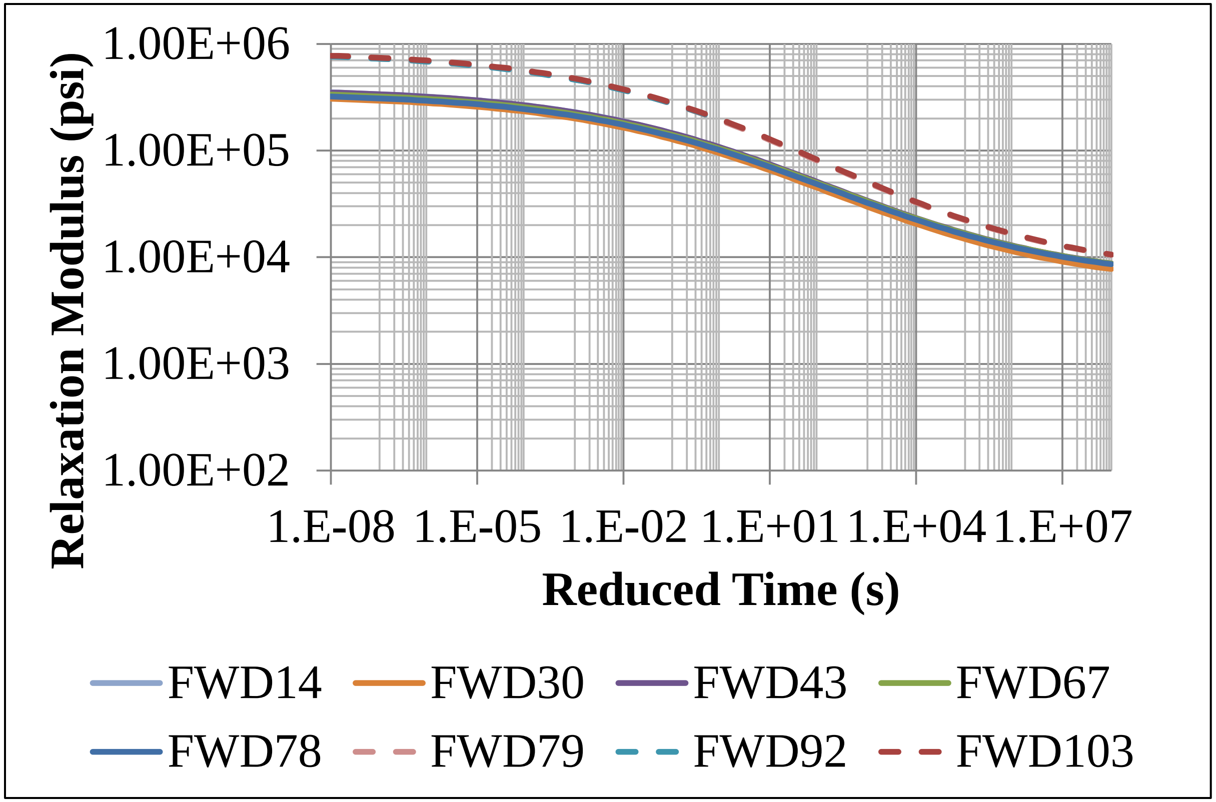
Figure 8: Daytime (High-Temperature) MPD (mm) vs. Location (mi.)

- RoLine laser used on PCC for IRI
- Spot laser used on AC for IRI
- High speed spot laser on AC for MPD

Dynamic back-calculations by Michigan State University

- Back-calculated multiple points in each section
- Some divided into sub-sections
- Relaxation modulus Et, complex modulus E*, shift factor
- No major differences day vs night

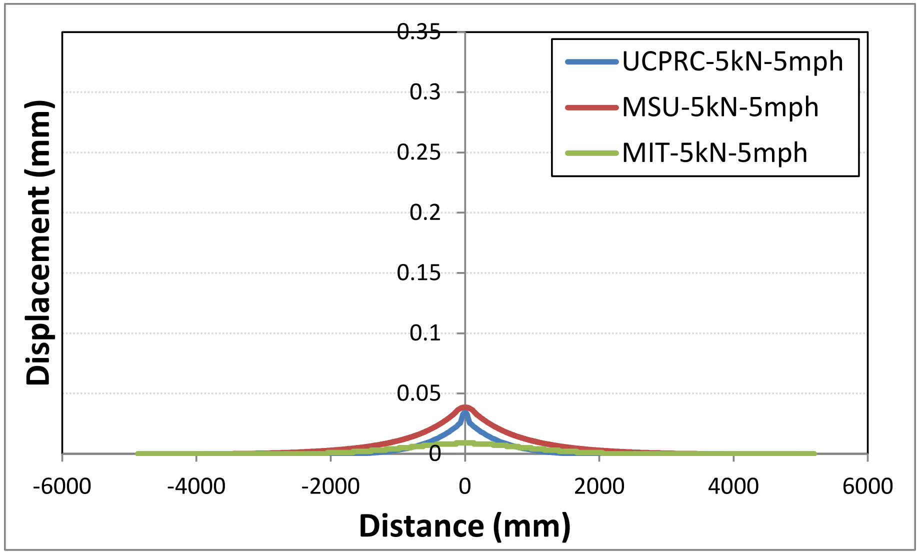


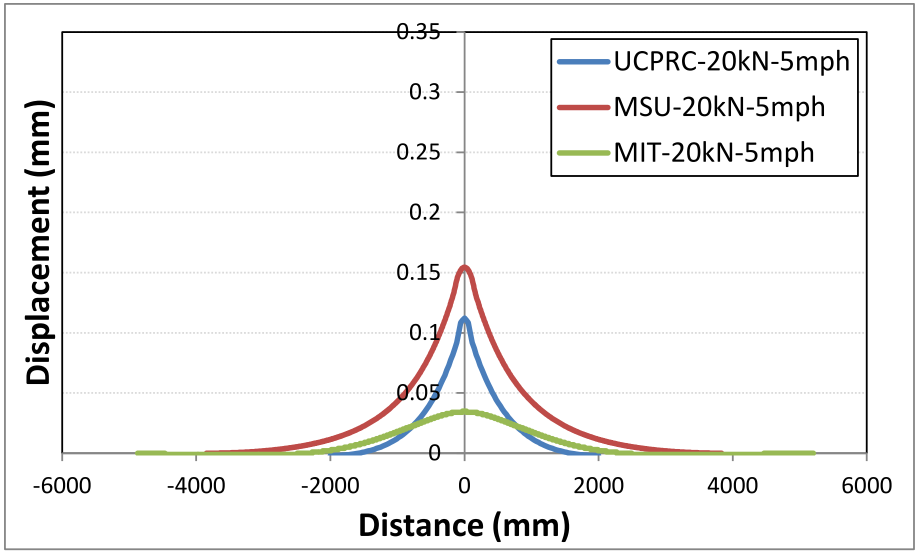


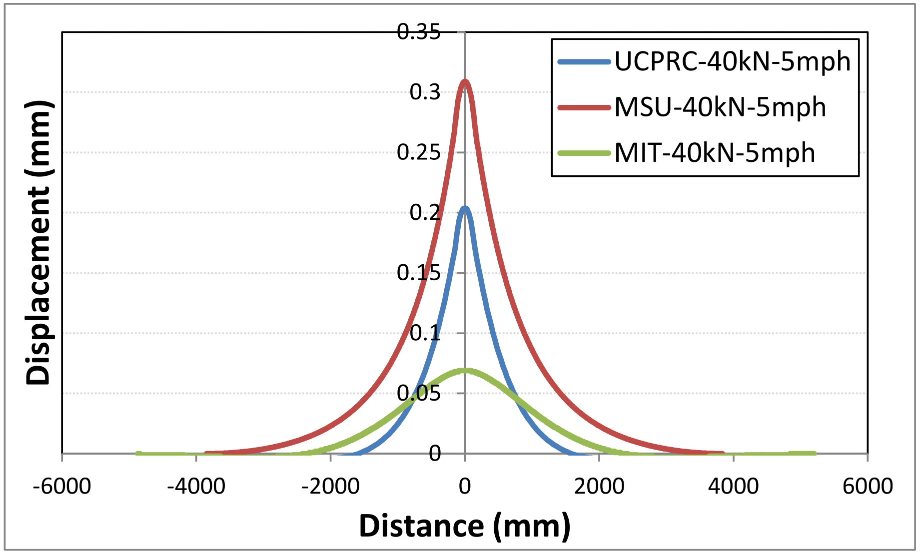
Analysis of initial two simple pavement sections for initial comparisons and for calibration of MIT model

- Back-calculations to develop master curve from day and night FWD tests
- Pavements
  - 3 layers all linear elastic, poisson = 0.35
  - 3 layers visco elastic surface, poisson = 0.35 one asphalt material master curve
- Two temperatures (20, 50 C) x two speeds (5, 60 mph)
- Vehicle information:
  - Single wheel, circular or square load, contact pressure = 700 kPa
  - Load = 5 kN, 20 kN, 40 kN
- **Outcome to report: shape of deflection basin and dissipated energy for each case**
  - Total cases: three elastic cases and twelve viscoelastic cases

Initial DISPLACEMENT COMPARISONS – ELASTIC
UCPRC shallow subgrade

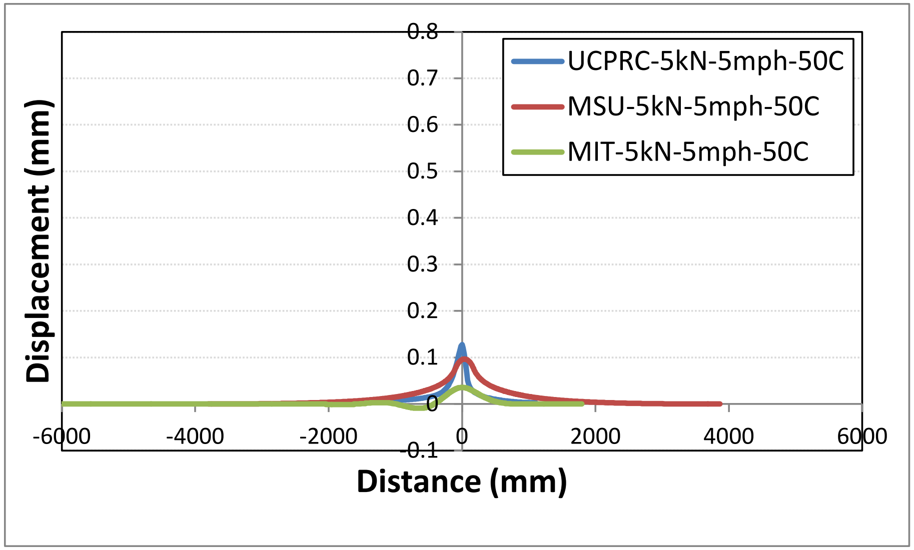


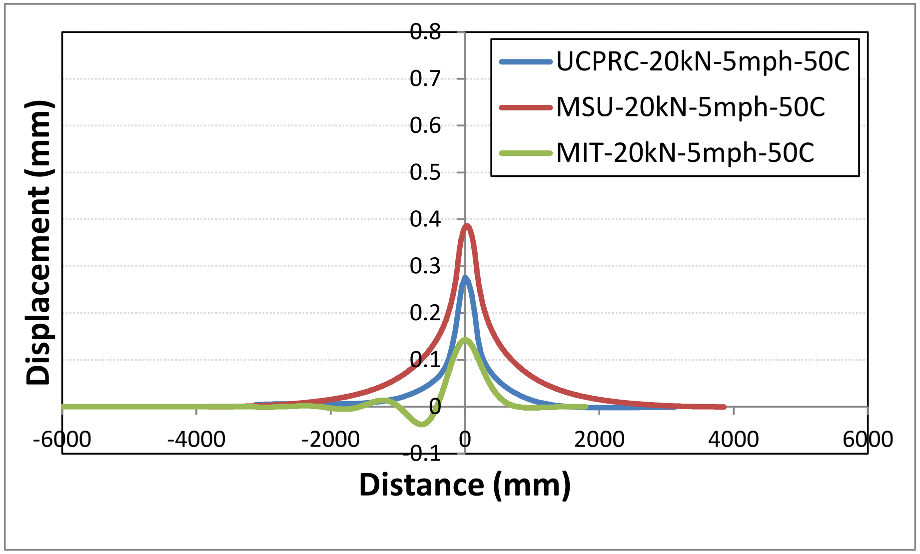


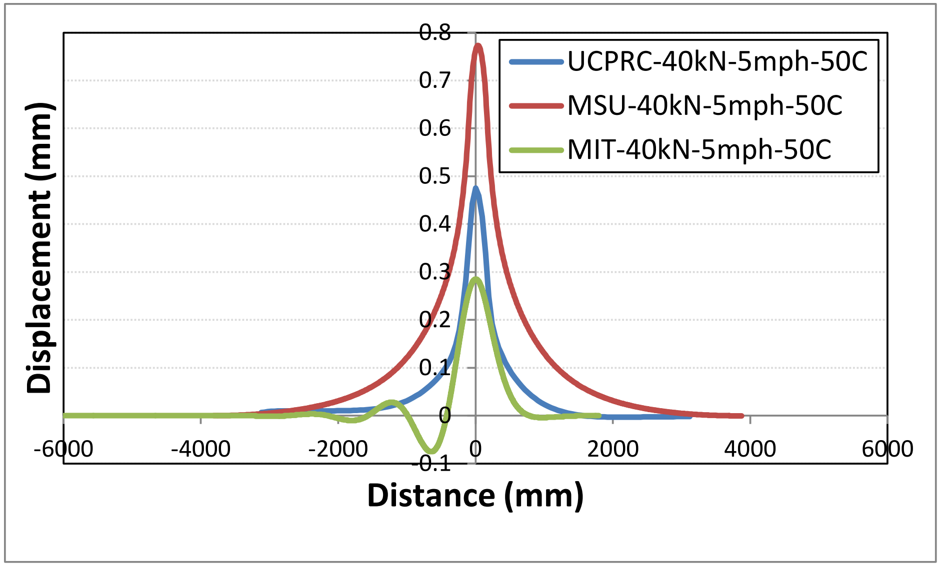


Comparison slides prepared by E. Coleri

Initial DISPLACEMENT COMPARISONS – VISCOELASTIC – 50C – 5 mph UCPRC shallow subgrade



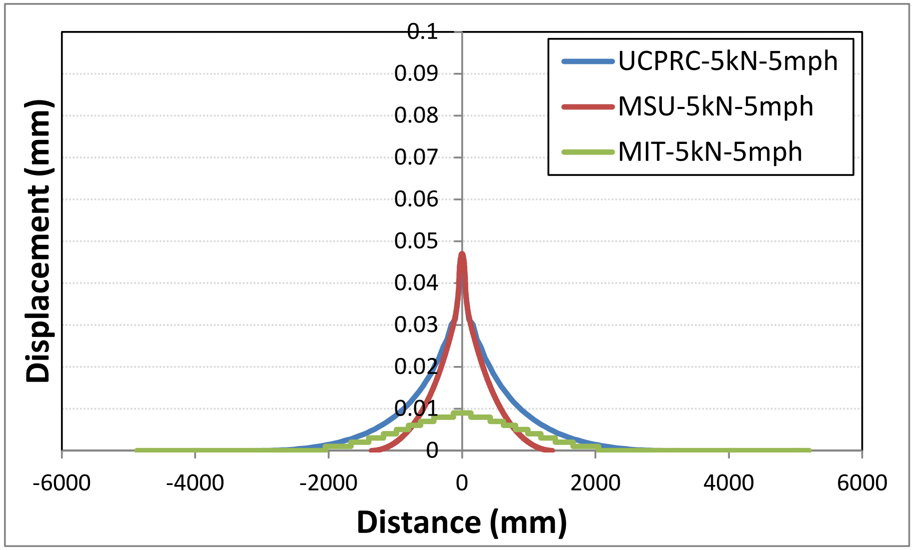


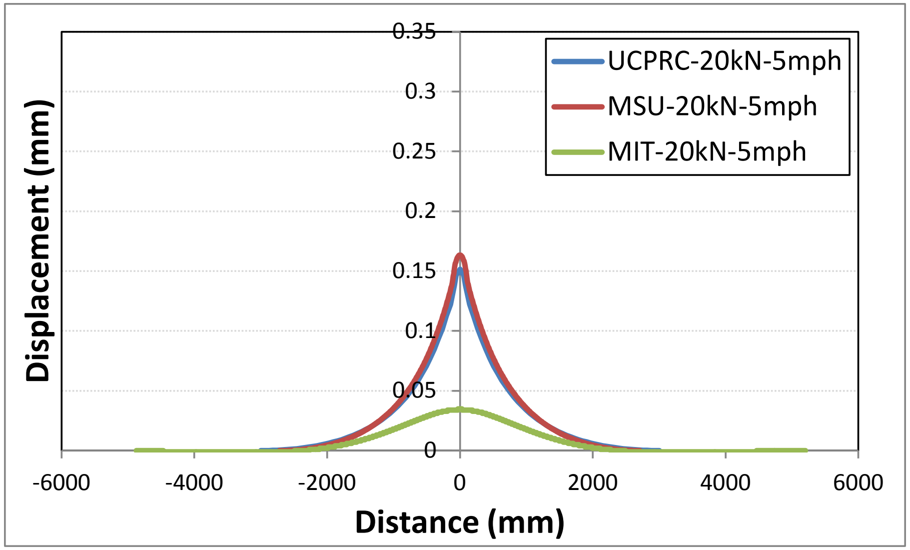


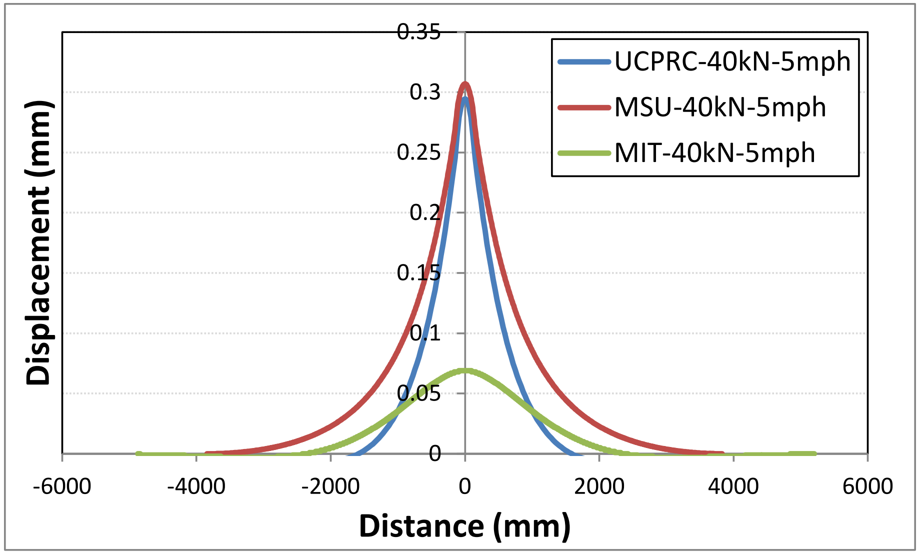
UCPRC change in subgrade thickness

- Changed from shallow subgrade used by Pouget to 5 m thick subgrade to better match semi-infinite subgrades of Michigan State and Layer Elastic Theory
- MIT using Winkler foundation

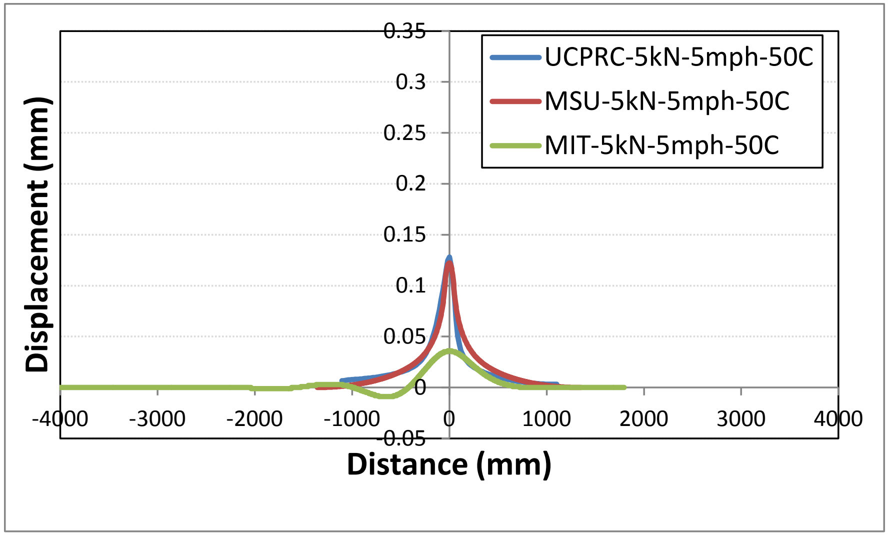
DISPLACEMENT COMPARISONS - ELASTIC

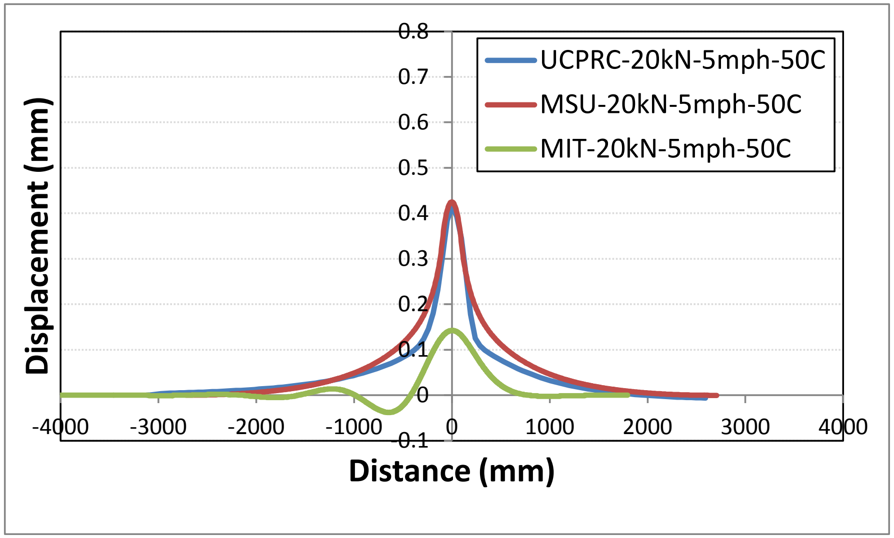


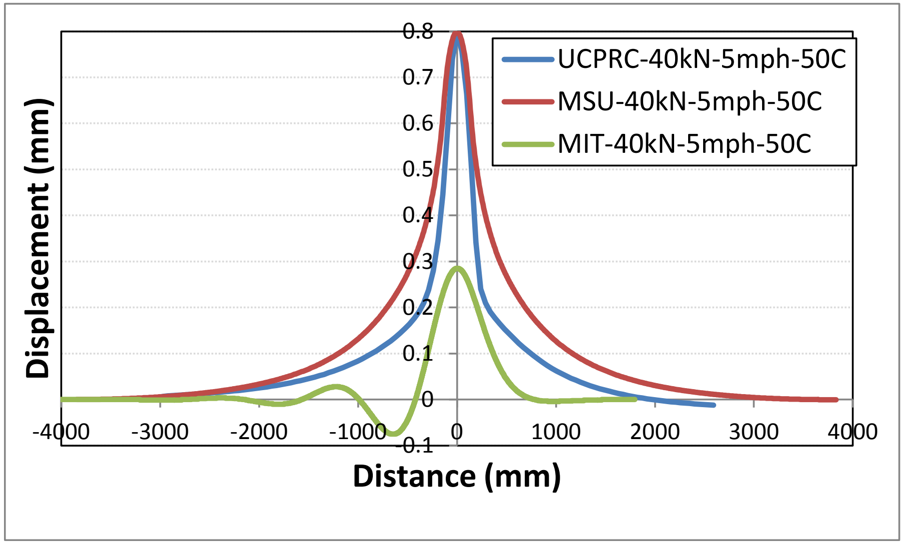




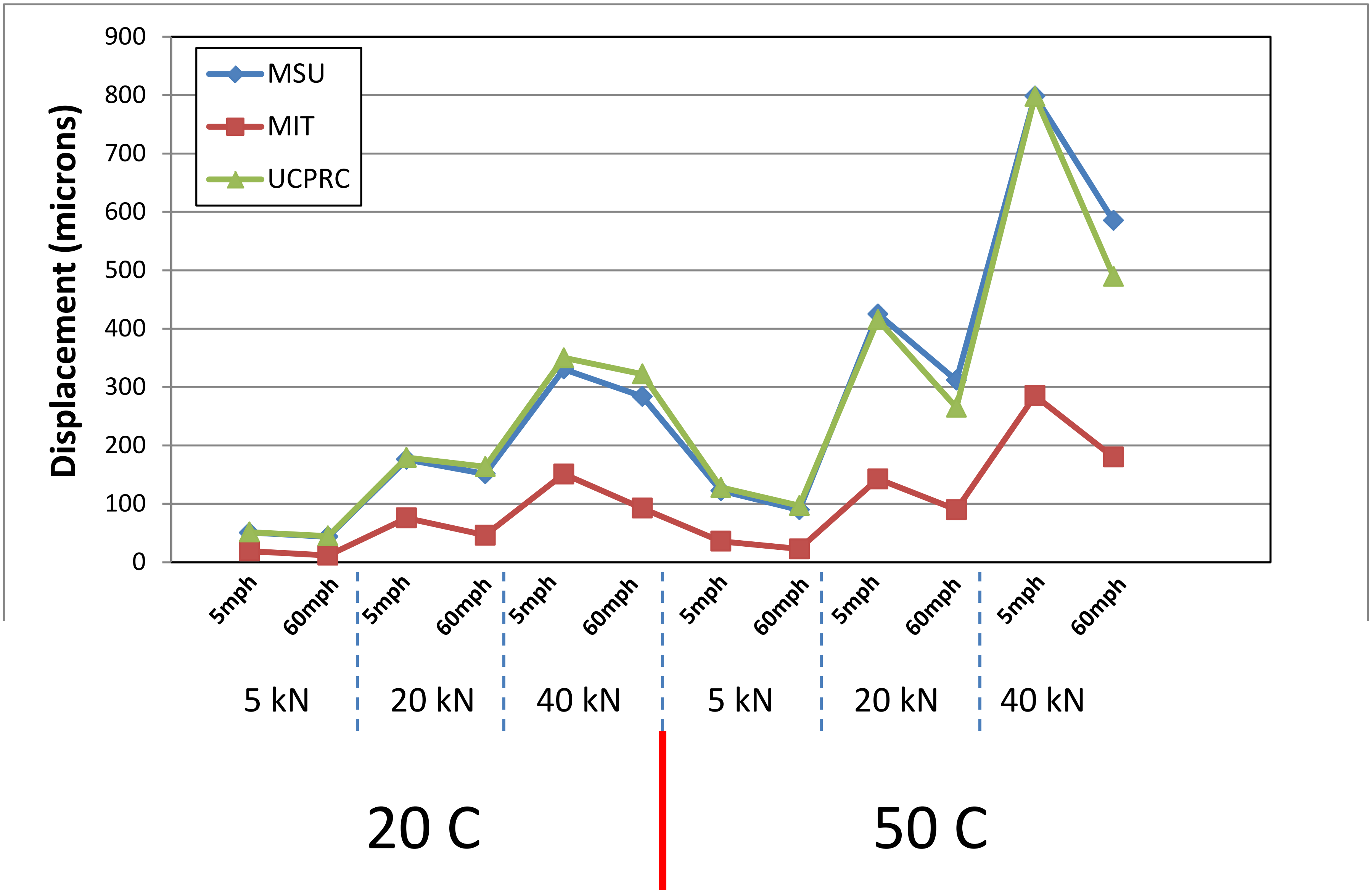
DISPLACEMENT COMPARISONS – VISCOELASTIC – 50C – 5 mph







PEAK DISPLACEMENT COMPARISONS



Excess fuel consumption measurements

- MIT and MSU are using equivalent gradient to calculate excess fuel consumption:

$$GR = 100 \times \frac{1}{n}\sum_{i=0}^{n-1}\frac{d_{i+1} - d_i}{\Delta x}$$

- GR = Equivalent Gradient in %

  d_i = The deflection at position x_i (m)

  Δx = Incremental $\left(x_{i+1} - x_i\right)$ (m)

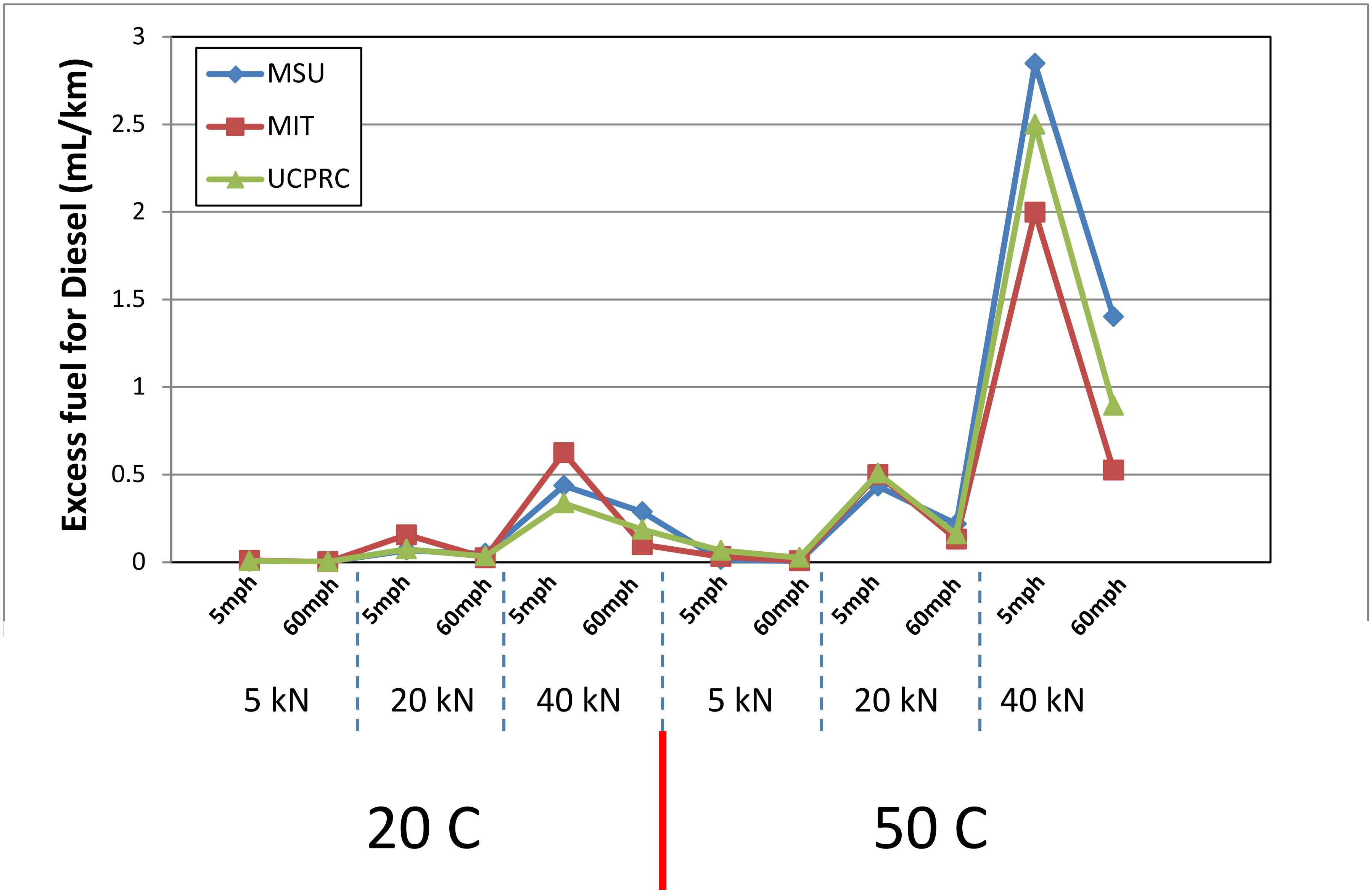
  n = The number of data points under the contact area $\left(x_{\mathrm{dmax}}, x_{(\mathrm{dmax+radius})}\right)$

- UCPRC is using strain-stress and phase angle:

(Pouget et al)

$$W = \iiint (\pi.\sin(\phi_E).\sigma_{0z}.\varepsilon_{0z}).dV$$

EXCESS FUEL CONSUMPTION COMPARISONS – Diesel



Factorial for analysis of results from field test sections

- **Speeds**
  - 50 km/hr (31.3 mph) , 100 km/hr (61.5 mph)
- **Temperatures**
  - One temperature at 1/3 depth in the total asphalt layers   30 C and 45 C
- **Factorial**
  - 3 vehicles x 2 speeds x 2 temperatures x Z structures (Z up to 22, start with 10)
- **Vehicles (use from NCHRP 720 study)**
  - Medium car, SUV, Heavy truck

Phase II: assessment of importance and potential empirical calibration

- Phase II will begin in December 2014
- Objectives
  - A: Using the calibrated models, calculate net annual excess fuel consumption for vehicles, traffic speeds, temperatures, pavement types (flexible, composite, semi-rigid, jointed concrete, continuously reinforced concrete) for California conditions
  - If results warrant, then:
  - B: Verify the same models using the results of field measurements on the same sections with instrumented vehicles
    - General approach used by Michigan State for calibration of HDM4 models for fuel use for macrotexture and roughness (NCHRP 1-45)